



Rage against the what? The machine metaphor in biology

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Received: 21 June 2023 / Accepted: 6 June 2024 / Published online: 1 July 2024
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Abstract

Machine metaphors abound in life sciences: animals as automata, mitochondria as engines, brains as computers. Philosophers have criticized machine metaphors for implying that life functions mechanically, misleading research. This approach misses a crucial point in applying machine metaphors to biological phenomena: their reciprocity. Analogical modeling of machines and biological entities is not a one-way street where our understanding of biology must obey a mechanical conception of machines. While our understanding of biological phenomena undoubtedly has been shaped by machine metaphors, the resulting insights have likewise altered our understanding of what machines are and what they can do.

Keywords Cybernetics · Neuroscience · Robotics · Xenobots · Philosophical methodology · Process biology · Non-linear dynamics, dynamical systems theory · Metaphor, Mechanism · Cells as machines · Brains as computers

SIR GALAHAD: Camelot!

LANCELOT: Camelot!

PATSY: It's only a model.

(Monty Python and the Holy Grail)

You insist that there is something a machine cannot do. If you will tell me precisely what it is that a machine cannot do, then I can always make a machine which will do just that!

(John von Neumann 1958; added emphasis)

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Introduction

Many find it useful to conceive of the cell as a factory (Alberts 1998) or mitochondria as the “powerhouse of the cell.” But there are also strong criticisms of the utility and validity of these technology-inspired metaphors, with the strongest criticisms arguing that ontological comparisons between machines and life are fundamentally flawed (Nicholson 2013, 2018, 2019; Holm and Serban 2021; Dupré and Nicholson 2018). Critics argue that machines are reducible to their parts and separable from environment, which is patently untrue of life. Thus, the *ontological* comparison (e.g., the powerstroke model for motor proteins; Nicholson 2019) between any machine and any organism or life process will necessarily fail a priori. For example, comparing DNA to computer code can and has misled researchers into searching for “the gene for X,” where X is any phenotypic trait. The ineffectiveness of hunting for “the gene for X” stems from an inappropriate analogy that likens computer code—seen as rigid, sequential commands—to DNA, which does not operate through such strict, line-by-line directives. Critics have not been fully successful in eliminating machine metaphors from the life sciences. Instead, debate has raged regarding the extent to which, if at all, entities such as computer code and DNA share sufficient similarities to serve as a meaningful basis for comparison. Participants in these debates have rallied to opposing positions: biological entities, such as organisms, *really can* be understood as similar to machines, or they *really cannot*. Both camps have exhaustively defined “machine.” However, we find these attempts to precisely define a “machine” to be the main issue: the ontological comparison of a specific machine to an organism or a life process requires a concept of what that machine *is*, and it is this *concept* of the machine that is being compared, not necessarily the real parts of it.

We argue that the distinction between machines as *physical entities* and machines as *conceptual frameworks* is crucial for understanding their metaphoric interplay with biological processes and entities. Drawing on recent philosophical and scientific discussions as well as historical examples, we dissect how our evolving notions of machines and life challenge traditional ontological divides. By ‘evolving notions,’ we have in mind the ways that some machines have been built as models of biological processes and how scientists have applied different ontologies to even simple machines. Rather than seeing machines and life as eternally separated by an ontological chasm, we highlight the dynamic, reciprocal shaping of our concepts, suggesting that machine metaphors enrich rather than impoverish our understanding of biological complexity. This, we think, undermines the critics’ stance that machines and biological processes are incommensurably distinct, opening the door to a more refined appreciation of how conceptual evolution reflects our intertwined technological and biological advancements.

In this paper, we argue that this is not a simple case of comparing apples to oranges; it is about juxtaposing the concrete gears and circuits of machines with the fluid, ever-changing ideas they symbolize. It is about recognizing that the features selected for any machine-organism comparison are chosen, not given, and that our understanding of biological entities and machinery *co-evolves*. There

is a reciprocal advancement in our concepts of what machines and life can do. This back-and-forth is not just academic in nature; it is practical, driven by our attempts to mimic life in our machines and understand living processes with machines. Critics might cry foul, claiming a fundamental mismatch between the living and the mechanical, but that seems a narrow view. The reality is more subtle. Machines, like living organisms, can be seen as more than the sum of their parts. As our concepts of both change reciprocally, so do the elements selected as relevant for comparison. Since machines are amenable in their conceptualization, we argue that machine metaphors do not imply any specific ontology. By appreciating the malleable nature of our concepts, we sidestep the stalemate of ontological debates. Far from being at odds, the metaphoric use of machines to understand life—and vice versa—shows that our grasp of both is enriched, not diminished, by this interplay.

We develop our argument by drawing on contemporary and historical instances where machine metaphors have been effectively employed. Our [“What is a machine? A twenty-first-century debate”](#) section examines the ongoing debate around machine metaphors, spotlighting two crucial points: first, the development of xenobots and autonomous robotics blurs the lines we once drew between the mechanical and the biological; and second, a thorough grasp of the inner workings of machinery fortifies our metaphorical toolbox. Here, the devil is in the details: what we know about machines and how we construct them is pivotal. Thus, shifting gears in our [“Metaphorical analogies in science”](#) section, we zoom out to the broader picture of metaphors themselves, arguing that metaphors do more heavy lifting than mere side-by-side comparison. They are at the *cognitive* core of a mutual give-and-take that shapes our comprehension of both domains within a historically situated framing. Our [“Reciprocity of the machine metaphor”](#) section then illustrates the reciprocal conceptual innovation of comparing machines and biological entities. We first go back to the cybernetic era’s analogy of living organisms to pendulums in complex systems before we move on to the brain-computer analogy (a comparison whose historical depth and sophistication far exceed the cursory shrug it often receives). We wrap up with a nod to the future in the [“Discussion”](#) section, advocating for a process ontology in biology with a positive outlook on the role of machine metaphors in developing that future.

What is a machine? A twenty-first-century debate

Critics caution that machine metaphors (hereinafter MMs) in biology are not simply stretching the bounds of metaphor, but are missing the mark entirely. Metaphors do not claim complete identity between two things. Yet, some contend that likening biological processes to technological concepts such as ‘programs,’ ‘information,’ or ‘computation’ to machines twists biological understanding out of shape (Dupré and Nicholson 2018; Nicholson 2019). This stance insists on a fundamental distinction between organisms and machines, with some voices going further to argue

that viewing nature through a mechanistic lens, as if it were merely a collection of machine-like entities, has led science astray (Sheldrake 2012; McGilchrist 2021).

In contrast, Bongard and Levin (2021, 2023) see a deep, ontological kinship between machines and organisms. Comparing their arguments, participants in this debate brandish different assumptions about the nature of machines and how biological phenomena can be understood. It boils down to how we conceive of machines in the first place, and these conceptions determine their role in biological exploration. Nicholson's exhaustive critique (2013, 2018, 2019, 2021) serves as our guide through this conceptual minefield as we navigate the implications for modern endeavors in robotics, synthetic and developmental biology. In essence, how we think about machines profoundly colors their utility in unraveling the mysteries of life.¹

Examples consulted by philosophers of biology about the use of MMs frequently center on old-fashioned gadgets, fixating on engineering metaphors drawn from the 'clunky' machinery of the Industrial Revolution—think typewriters, looms, and steam engines, as noted by Levy and Bechtel (2021, 99).² Yet, the debate on MMs per se in biology must take account of modern technology. Bongard and Levin (2021) countered the critics, pointing out that the skepticism towards MMs often springs from an antiquated view of what machines are and can do. They argue that as technology evolves, so does the applicability of MMs, compelling us to revisit and rethink what distinguishes mechanical from biological, suggesting that our metaphors need to keep pace with our inventions.

Key terms such as machine, robot, program, software, evolved, designed, etc., need to be revised in light of technological and theoretical advances that have moved past the dated philosophical conceptions that have limited our understanding of both evolved and designed systems.

As Bongard and Levin challenge us to recalibrate our metaphors in tandem with technological progress, we pivot to Nicholson. Nicholson unfurls three tightly knit arguments against the ontological use of MMs in biology, drawing sharp lines between the living and the mechanical. These arguments lay the groundwork for understanding the core points of contention in this debate, marking a shift in our discussion from the potential of MMs to the challenges they face when applied to the living world. We discuss each in turn.

Purpose and agency

Nicholson (2013, 2018), tipping his hat to Monod (1974), distinguishes between the extrinsic purposiveness of machines (design) and the intrinsic purposiveness of organisms (teleology), marking the battleground of our first major dispute. '*The argument from teleology*' is based on the understanding that while machines are

¹ Machine metaphors are in focus here, not causal-mechanistic explanations in science (Craver and Tabery 2015).

² Levy and Bechtel (2021) suggest separating machine from causal-mechanistic explanations in response to Nicholson.

designed, life evolved. Biological processes are self-organizing, whereas machines are assembled. Nicholson (2013, 671) stressed: “organisms, unlike machines, are not only organized but are also self-organizing and self-regenerating systems ... in an organism, the parts are not just there for the sake of each other, but they also produce each other, maintain each other, and generally exist by means of one another.” Teleology has been historically foundational to organismal thinking (Toepfer 2004). This self-driven purpose sets life apart—or so it seemed until xenobots and synthetic life blurred the lines, challenging us to rethink where we draw the line between the born and the built (Kriegmann et al., 2020; Blackiston et al. 2021).

Xenobots are not your garden-variety synthetic organism but an unprecedented fusion of African clawed toad embryonic stem cells sculpted by algorithms into a menagerie of forms. This calls for a radical inquiry into the boundaries of multicellularity, as these xenobots, a blend of biological raw material and digital blueprint, defy traditional organic design by self-organizing into motile, evolving entities. They are not just tweaked organic matter but represent an emergent class of beings that redefine themselves through their actions, not just their lineage or evolutionary heritage. They develop into various forms *on their own*. In response to these findings, the evolutionary biologist Jablonka (who “was not involved in the work”) considered “xenobots nothing less than a new type of creature—one ‘defined by what it does rather than to what it belongs developmentally and evolutionarily’” (Ball 2021).

Xenobots—and other biobot research—problematizes Nicholson’s argument from teleology with an ontological challenge. The quagmire lies with agency, a concept entwined with the very essence of intrinsic purpose in organisms. Agency, in its most basic form and linked to self-governed behavior, may be characterized as “a set of capacities detached to some extent from their prior evolutionary history by which they actively and creatively sustain their integrity and behavior” (Newman 2022). Newman, a developmental biologist, noted that xenobots, with their self-directed development and built-in purpose *sans* evolutionary backstory, are upending traditional notions of life. His analysis shows intrinsic purposefulness “is not unique to animal or holozoan cells, but pertains to all forms of cellular life,” including bacteria, synthetic cells, or biobots like xenobots. The upshot is that hybrid entities like biobots exhibit developmental capacities and autonomy (as autopoiesis or “organizational closure”), traditionally attributed to organisms, and now sufficiently blurring a categorical distinction between organisms and cellular machines.

Non-linear dynamics and processualism

‘*The argument from thermodynamics*’ (Nicholson 2018) states that, unlike the predictable, static working of machines, organisms are in a vibrant dance with entropy, dynamically exchanging energy to keep disorder at bay. This notion props up the organicist view of biology as a realm of processes, not static entities (a stance championed by Dupré and Nicholson 2018; Dupré, 2021). Put simply, while machines sit neatly arranged in their linear, compartmentalized world, life thrives in a messy, self-organized cosmos of complexity, eschewing linear, modular, and hierarchical

constraints. Dupré and Nicholson (2018) throw a critical eye on seemingly simplistic, mechanistic models of life, highlighting the vibrant dynamism that defines biological processes in stark contrast to the ‘stable parts’ picture of machinery.

Dynamical Systems Theory (DST) pushes back. Self-organizational capacities of organisms are increasingly modeled via the mathematical framework of DST (e.g., using fractal designs)—which, not by coincidence, has been successfully applied in robotics and the design of organismically-behaving machines (Pfeiffer and Bongard 2006). For instance, cutting-edge machine design, leveraging DST, paints robotic agents not as assemblies of parts but as cohesive, interactive entities. Consider the task of crafting robot limbs—one must understand their functional integration and interaction within the robot’s overall body and environment. The question is not just “How many legs?” but “How do these legs work together, and how do their movements influence this specific leg?” as well as “What materials are used, and what interactions are predicted for what movement on what surfaces?” (etc.). Modeling the dynamics of machines and biological processes is not as categorically distinct as critics allege. Sure, a robot’s steel leg doesn’t biodegrade outside its chassis like a liver would outside the body, but that’s a matter of materials, not ontology. Through the lens of DST, if you yank a leg off a robot, it stops being a “leg” in the functional sense—just a piece of steel, devoid of its role in locomotion. Modern robotics shows us that parts can shift roles and identities within the whole, challenging the static view of machines versus the dynamic nature of biological systems.

Organicists may object, focusing on a deeper ontological divide than how we understand and utilize models in science. But this stance might misinterpret the mindset of those knee-deep in robotics, and the MM critic is in danger of assigning an ontology to machine modeling that roboticists do not share. For example, Bongard and Levin’s (2023) ‘*argument from polycomputation*’ posits that adaptive behaviors and functions within biological systems can be understood as materials undergoing concurrent computational processes without a unified objective. Like Nicholson and Dupré, they consider life a web of interconnected, multi-layered and multi-scaled processes. Polycomputing involves coupled and coordinated multiscale behavior through the same physical medium, a concept neuroscientists and biologists know all too well (e.g., coupled neural oscillations and gene regulation networks): “For example, the same ion channels that are used for physiological control of cell homeostasis and metabolism are used *simultaneously* in large-scale bioelectric circuits that compute the direction of adaptive changes in growth and form in embryogenesis, metamorphosis, regeneration, and cancer suppression” (Bongard and Levin 2023, original emphasis). Polycomputation and related concepts are increasingly employed in material science, engineering, and biological cognition frameworks—making the idea of machinery made of bits and bobs bumping along with their own functions seem archaic to modern modelers. Machine modeling and process ontologies can coexist; moreover, their ontologies are not only compatible; they are complementary.³

³ For completeness, Nicholson’s (2021) third critique, ‘*the argument from scale*’, highlights how the minuscule scale of fundamental organismal processes permits a range of interactions and material properties distinct from those seen in the larger-scale components of machines. Militello and Moreno (2018)

Contemporary debates about the application of MMs in the life sciences reveal that conceptions of machinery are not set in stone but rather subject to change. This fluidity suggests that critiques levied by MM skeptics may not hold water when applied to biological models that incorporate notions of modern machinery. (See our “[The pendulum: from simple machines to non-linear dynamical systems](#)” section on how this all stacks up against old-school machinery.)

Metaphors of metaphors?

For some critics, the real snag is not merely the motors and circuits of today’s tech but a deeper issue—a certain engineering *mindset* that could tempt biologists into blurring the lines between gears and genes, machine and organism. Nicholson zeroes in, spotlighting the overlooked pitfalls of slapping an engineering perspective onto biology, armed with (and against) the writings of historical thinkers like Monod (1974). He is poking at the idea that while you can break down biological functions into machine-like operations (think bending joints or DNA unzipping), it is the messy, stochastic, and inherently chaotic nature of life—like the often overlooked yet crucial role of ‘noise’—that truly sets the living apart from the inanimate: “In engineering contexts, noise refers to an unwanted random disturbance that hampers the perception of a transmitted signal” (Nicholson 2019).

This concern holds considerable significance, given that biologists, who are generally not trained as engineers, cannot simply impose an engineering framework on biological phenomena. They lack the intricate knowledge of machine complexity that might make such a comparison valid. Engineering involves knowledge and reasoning processes distinct from everyday ‘intuition’ or other specialist domains such as biology (Lazenbnik 2002). Biologists thus lack an understanding of machine complexity that might make MM comparisons valid (unless they *also* are engineers!). Instead, biologists often rely on a layperson’s understanding of machinery, leading to comparisons that might miss the mark on how machines—or cells, for that matter—actually operate. Nicholson (2019, 123) hits on this point, noting that everyday familiarity with machines might lend MMs in biology a veneer of commonsense credibility—after all, machines seem to work this way, so why not life?

We agree with Nicholson that surface-level understanding of machinery can be misleading. Machines surround us, yet our grasp of their inner workings is mostly a cozy hubris in our general knowledge, leading us to overestimate our understanding—a phenomenon known as the “illusion of explanatory depth,” which explains that people “feel they understand complex phenomena with far greater precision, coherence, and depth than they really do” (Rozenblit and Keil 2002, 521).

Yet we think that the debate should move beyond the question of whether biology can be mechanized in our models and ask whether our models—and our understanding of machines themselves—are up to the task. In diving into

Footnote 3 (continued)

offer a rebuttal by shedding light on the structural conditions that govern the operation of microscopic machines.

this question, we prod deeper than the suggestion from Calcott et al. (2015) that models in engineering can be useful in biology and vice versa. We agree that these metaphors have practical utility. In this paper, however, our focus remains steadfast on the ontological comparison between machines and life as conceptualized through MMs. Despite any utility of any model, the MM critic can simply respond that utility has no bearing on ontological similarity—we, however, really do believe that machines and life can both be conceived of as processes, and we believe that engineers often think that way of their own machines.

In the broader discourse on MMs, the “illusion of explanatory depth” often fosters a type of intellectual complacency regarding machines—a complacency conspicuously absent among those who navigate both biology and engineering. Enter biologists like Levin, who, armed with engineering acumen, sidestep the common pitfalls of oversimplification. Such work exemplifies how deep familiarity with machines and engineering allows one to draw comparisons between particular machine and life processes *without* simplifying the machine down to a pile of moving parts (which would be a caricature of itself, and only one of many possible representations). This prompts us to revisit our concept of what it means to ‘mechanically model’ biology. If non-experts are drawing comparisons with caricatures, let’s see what experts are doing.

As we grapple with engineering jargon that has seeped, unbidden but not unwelcome, into the life sciences, we are invited to hone our philosophical instruments. This jargon, dismissed by critics, may harbor more insight and utility than expected. To make this point, we take a closer look at Nicholson’s critical interpretation of Bray (2009), exploring the potential reasons behind his ungenerous reading. Bray (2009) advocated for understanding every cell as a computing unit—a concept Nicholson (2019) found stale, noting how our cell theory hasn’t really evolved despite decades of scientific leaps: “It is quite remarkable to observe that, despite the enormous empirical advances that have been made since 1962, our basic theoretical picture of the cell has remained essentially unchanged (see, e.g., Bray 2009...).” However, upon closer inspection, it is remarkable to observe that Bray’s (2009) conception of cells and their genetic underpinnings seem to echo Oyama (1985 [2015]) far more resonantly than they do Blow’s (1962) somewhat dated portrayal of DNA, which Nicholson finds problematic. This matters, as Oyama elegantly criticized the use of technological concepts such as ‘programs’ in genetics because they erroneously attribute genes with centralized intrinsic causal powers that direct organismal development. Oyama (1985 [2015], 26; original emphasis) favored an interactionist view that blurred the difference between internal and extrinsic causes (genetic versus environmental):

Organismic form... constant or variable, is not transmitted in genes any more than it is contained in the environment, and it cannot be partitioned by degrees of coding or by amounts of information. It is constructed in developmental processes. What are transmitted are macromolecular form, which, though it is necessary for the development of phenotypic form, neither contains it nor constitutes plans for it, and *developmentally relevant aspects of the world*.

Oyama is a far cry from Blow's analogy, which rather quaintly pairs computers and cells:

a large computer would be the control mechanism [of the cell] ... in its store would be an encyclopaedia of programmes which would give the proper response to all possible sets of external circumstances ... Output from the computer would go ... to a set of automatic machine tools which would perform the various operations required for construction of a duplicate factory. Here the complex task of converting the information stored in the computer into solid matter would be performed (Blow 1962, p. 177; qtd. Nicholson 2019, 109).

Now stack up Bray's view against Oyama and Blow:

From a time-compressed view, the sequences and structures of RNA, DNA, and proteins can be thought of as continually morphing in response to the fluctuating world around them... It is as though each organism builds an image of the world—a description expressed not in words or in pixels but in the language of chemistry. Every cell in your body carries with it an abstraction of its local surroundings in constellations of atoms. A basic knowledge of and response to the environment are integral parts of every living cell's makeup" (Bray 2009, x).

Sure, the theoretical landscapes inhabited by Bray and Oyama are distinctively separate. But let's get something straight: Bray had not been cryogenically frozen since 1962. His deployment of tech-speak, particularly the language of computing, to delineate cellular activities hints at a nuanced duality in the use of description. Bray confidently wades into the mechanistic talk—speaking of motors and gears—that Nicholson eyes warily. Nicholson appears to assume that, when he uses computing language, Bray is referring to laypersons' understanding of computers as a device that only performs the instructions embedded in the programs within them. But it is easy to see that Bray was not comparing hard drives to DNA. His comparison between cell and computer was one of *processing* and *procedure*, not *compositional* similarity. Bray (2009, 232) says himself:

If a living cell were no more than a watch or other piece of machinery, I would have little more to say. I could simply make a list of the parts, describe each one, and indicate how it connects to the whole. The list would be long, but in principle, if you studied it carefully, you would eventually understand how the cell works. ... But we know that this is not possible. Whatever resemblance a living cell might have to a watch, it is unlike any timepiece made by human hands. This watch is soft and deformable—a Daliesque watch that melts onto its surroundings, one that can adopt more designs than you will find on Macy's Web site.

Bray's engineering perspective veers closer to Levin's cross-disciplinary vision than Nicholson's philosophical words of caution, with Bray making a deliberate connection between his analogies of machinery and the forefront of robotic

research. Terms like motor or computer effectively stand for processes, not specific devices, such that a computer represents *any* entity *doing* computation (a human, a loom, a PC). This is not about likening cells to computers because they share nuts and bolts but because they both engage in a comparable *processing task*.

This leap from mechanical likeness to functional parallelism invites a deeper philosophical reflection: it compels us to reassess the biologist's conceptual toolkit for comparing the animate with the inanimate, urging a move towards a more abstract understanding. Computers could be described as having circuit boards and spinning discs. They may also be characterized in terms of logic gates and signal integration in digital computation, or as continuously varying signals or quantities that directly correspond to the physical variables in analog computation. (See "[The computational brain: machines as theories](#)" for the notion of computation as a process.) Here, we encounter two distinct interpretations of 'computer,' each reflecting different ontological views of what seems to be the same entity. To criticize one version by applying the principles of the other reveals a basic misunderstanding.

A failure of successful metaphors?

It is clear at this point that a thorough battlefield is drawn between those in favor and those against MMs in the life sciences, with each side operating from distinct philosophical grounds and visions of what the conceptualization of machines entails. So, what is our position on this?⁴

Critics raise compelling points. The portrayal of biological entities *can* fall prey to outdated MMs, which subsequently take on a life of their own, both experimentally and conceptually. Their skepticism towards MMs is not merely a critique of selecting inappropriate metaphors based on a superficial understanding of machinery, though. Rather, it signals deeper philosophical discontent. Critics further contend that previously successful MMs are failures.⁵ For example, the simplistic correlation between genotypes and phenotypes, likened to a "blueprint" analogy for organisms, illustrates a broader critique. One might argue that all models eventually reach their conceptual expiry date, but this perspective does not suffice to address critics' concerns. They advocate for a fundamental shift in perspective, akin to the Copernican revolution, moving from a geocentric (machine-centric) to a heliocentric (organicism-centric) view in biology. Indeed, they see MMs as biology's version of sticking with a geocentric view when we should be orbiting around organicism. Sure, geocentric models could predict cosmic events with remarkable accuracy. But being useful back then did not make it right. Similarly, MM critics highlight discrepancies in observational accuracy

⁴ We appreciate a reviewer's blueprint metaphor prompt to clarify our perspective.

⁵ Consult Holt et al. (2021) for their interpretation: Across the expansive narrative of Western history, each generation's introduction of new machines has perpetually supplied novel metaphors of mechanization, effectively delaying a significant shift in conceptual understanding. Even Hippocrates subscribed to a mechanistic worldview (note that the reference they provide for Hippocrates' alleged ontological mechanism (Jouanna 2012) addresses neither mechanism nor machines).

(where MMs fail to capture the distinctive features of living systems fully), technological advancements (which enable a more direct examination of biological processes beyond static models), and the existence of powerful theoretical alternatives (such as organicism, which reveals aspects of living systems that MMs might obscure or misrepresent), urging a paradigm shift in the conceptualization of biology.

We cannot brush off this call for a seismic shift in thinking with a casual “Every model has its expiration date.” However, we are also pitching a game-changing perspective, one that flips the script on the MM critics’ unexamined assumptions. Our version of a Copernican revolution zeroes in on what we even mean by “machines.” MM critics have taken the definition of a machine as a constant, a stable benchmark, to argue that our mechanical metaphors fall short of capturing biological ontology. We challenge this stance by treating the concept of machines—and, by extension, MMs—as malleable, asserting that our understanding of machines is just as subject to (r)evolution and reevaluation as our understanding of biological systems.

Consider another analogy from physics, the three-body problem. The crux of the three-body problem is to predict the positions and velocities of three celestial objects over time based on their starting points, speeds, and masses. These bodies are thought to tug at each other gravitationally (in line with Newton’s law of universal gravitation). This gravitational dance is governed by a series of differential equations mapping out their trajectories. The headache with the three-body problem is that the gravitational pull between any two bodies hinges on their ever-shifting distance apart, knitting together a dynamic that is anything but linear and defies any straightforward, catch-all solution. In the context of our discussion, we are navigating a terrain with three shifting variables, not just two:

- (1) The evolving conceptual understanding of organisms (and other biological phenomena),
- (2) The evolving conceptual understanding of what constitutes a machine (and its capabilities), and
- (3) The evolving metaphorical frameworks that describe their relationship (focusing on certain features and behaviors, and scaffolded by the available techniques and social conditions under which scientific modeling operates).

Trying to dissect any two of these variables without considering the impact of the third overlooks their true complexity. Hence, deciphering how (3) influences (1) necessitates grappling with the evolving dynamics of (2).

Up to this point, we have elaborated on different perspectives regarding (1) and (2). The next phase of our discussion turns to the dynamics of (3). We begin by analyzing the cognitive significance of metaphors within scientific inquiry in our “[Metaphorical analogies in science](#)” section, focusing on the attributes that empower metaphors to influence the direction of scientific investigation and further foster their own transformative journey.

We then engage with two concrete examples of historical and contemporary shifts that illustrate the malleability of (3) by emphasizing the reciprocal innovation between technological and biological understanding. These cases illuminate the synergistic augmentation between our conceptualizations of machines and our grasp of biological phenomena. They specifically highlight how the metaphorical relationship unfolds, showcasing how technological and biological insights mutually scaffold and enhance the framework in which they are deployed.

Metaphorical analogies in science

Metaphors hold a pivotal role in the scaffolding of scientific thought. In “Models and Analogies,” Hesse (1963) explored the powerful role of metaphors in not merely bridging but actively constructing parallels, echoing Black’s (1962) insight that metaphors serve as cognitive tools, much like telescopes that reveal previously invisible stars. For Hesse, metaphors are foundational in scientific inquiry, reshaping our understanding of phenomena under investigation. The use of metaphors in science resembles a creative act of drawing connections, rather than simply uncovering existing ones, echoing Black’s assertion that metaphors themselves craft the similarities they depict. In essence, rather than uncovering objective similarities, metaphors *actively generate* them.

Accordingly, metaphors are not passive representations of things in the world. Especially feminist scholars have highlighted how certain metaphors, once embedded in the fabric of scientific practice, start to dictate the narrative, becoming “part of the logic of science itself” (Stepan 1986, 274). The quandary arises when socially charged metaphors seep so thoroughly into scientific vernacular that they smuggle in underlying biases, leading to misconceptions about natural phenomena and perpetuating societal ills like sexism and racism within scientific contexts (Sullivan-Clarke 2019). Here lies the delicate entanglement of a metaphor’s intellectual role and its societal underpinnings.

Exploring the socio-historical context alone does not completely capture the cognitive role that metaphors play in science. This function demands its own analytical lens, focusing on its distinctly *cognitive* role in shaping scientific models (Holyoak and Thagard 1995). Unlike casual metaphors peppered through everyday speech, scientific metaphors are fundamentally *methodological*, crafted with precision and purpose. They are not “a trivial extension of metaphors in ordinary language” (Cat 2001, 397–8). Metaphors construct a dyadic relationship: a carefully selected metaphor lays down a conceptual bridge to a target system, inviting us to traverse its landscape through the metaphor’s lens. Following Hesse’s lead, engaging with metaphors in scientific thought means untangling a web of intuitive associations and organizing them into a coherent theoretical framework that aligns two analogs. By carefully charting ‘horizontal parallels’—the shared features between metaphor and target—we pave the way for ‘vertical’ leaps of logical inference about how they might causally connect (Fig. 1).

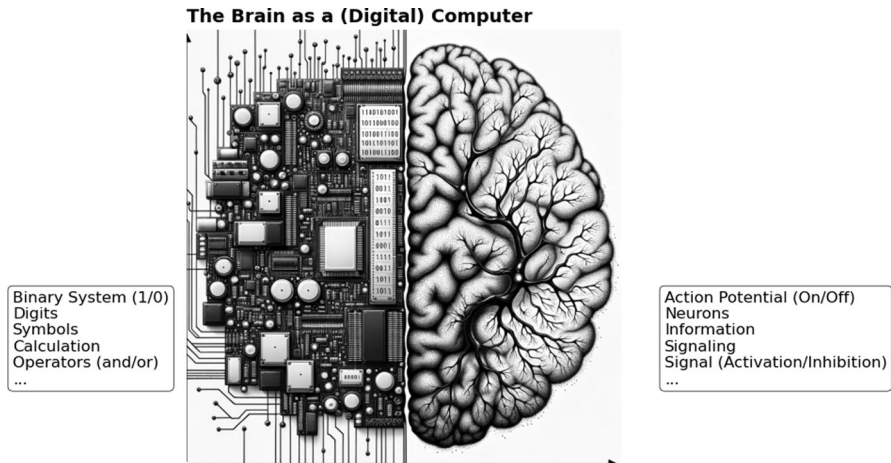


Fig. 1 (co-created with DALL-E): Exemplification of a scientific metaphor according to Hesse (1963), using an analogous relation between computational systems and the brain (after McCulloch and Pitts (1943) in Piccinini (2004)). Horizontal parallels express similarity relations; vertical rows represent possible causal connections

Hesse's breakdown of scientific metaphors is crucial.⁶ Metaphors navigate through three types of relationships: the shared positive analogies, the unshared negative analogies, and the undecided neutral analogies. Take Dalton's model, akin to billiard balls, which robustly supported his atomic theory. Attributes of billiard balls that align with our understanding of atoms and gas molecules represent a positive analogy, while those attributes that diverge form a negative comparison. Then there's the neutral analogy, covering billiard ball characteristics that might—or might not—mirror those of gas molecules. It is this neutral analogy that fuels the engine of scientific discovery. We suggest that this fertile territory of metaphor has its own *iterative* and *reciprocal* dynamics with how we conceptualize the interplay between biological phenomena and machines.

Evaluating scientific metaphors demands a look not just at their past utility but, crucially, at how they inspire fresh lines of inquiry and methodological shifts in research. In the thick of the MM discussion, Nicholson and fellow skeptics raise a valid point: the straightforward comparisons between machines, as we ordinarily know them, and the complexity of life fall short. Feminist critiques have similarly underscored the pitfalls of leaning too heavily on positive analogies, highlighting the risk of misunderstanding the very phenomena we aim to understand. Feminist scholars and, later, Nicholson illuminate the perilous territory of mistaking negative analogies for their positive counterparts. This misstep is not merely a semantic oversight but a conceptual pitfall that can skew our understanding and interpretation of scientific phenomena, leading us down a path of flawed reasoning and misguided conclusions. Sure enough, their warnings resonate deeply with our

⁶ Detailed examination of Hesse in Chen (2020).

focus on dissecting the cognitive architecture underlying metaphors. But we pivot attention to neutral analogies as catalysts for significant scientific progress. It is likely that many critics would acknowledge the ongoing utility of MMs. However, we propose that *the value derived from neutral analogies is augmented by shifts* in the positive and even negative analogy, shifts that reflect our changing understanding of what machines are and can do.

Our understanding of machine capabilities and actions changes in tandem with our discoveries about biological processes. Our ideas of what machines *can do* change alongside what we find life *is doing*.

This iterative process in the analysis of scientific metaphors presents itself in a dual fashion. On one hand, *pace* Chang (2004), scientific modeling with metaphors experiences a kind of *epistemic iteration* (or evolution), where both the metaphor and its deployment are refined and reshaped: “scientists also interpret and collect data in support of the conclusion of the analogical argument. The modified version of the metaphor—one that has the new information added to its positive or negative analogies—guides the community further, motivating new analogical arguments that contain the previously incorporated information in its premises” (Sullivan-Clarke 2019, 158). On the other hand, we highlight that the refinement of analogous relationships is not just a linear progression. It involves an adaptable and dynamic approach to selecting the traits we use to forge these conceptual analogies. We want to keep this point in mind as we move forward.

Despite whatever machines *are* and *do* at any given moment, what ultimately matters in a metaphor are the aspects of the machine that are selected as constitutive of it. There are two co-existing layers of semantic fluidity: on one level, the term ‘machine’ can embody a plethora of meanings and interpretations *synchronously*, meaning at any given moment (as discussed in “[What is a machine? A twenty-first-century debate](#)”); on another, the specific characteristics we choose to spotlight may shift in unexpected ways over time, or *diachronically* (as explored in the “[Reciprocity of the machine metaphor](#)” section). In each instance, the positive and negative analogies linking the objects of analysis undergo transformation, leading us to pose new inquiries (neutral analogy).

Reciprocity of the machine metaphor

The core idea advanced in this section is that the notion of machines as fixed, unchanging constructs is a misconception. Much like the living systems they are often compared to, the characteristics and theoretical models of machines are malleable, shaped not by their inherent nature but by the perspectives and methodologies scientists apply to them. This perspective diverges sharply from the view presented by Holt et al. (2021, 2), which suggests that despite technological advancements, the essence of the machine analogy remains unchanged: “Although the machine analogy would continue to evolve as technology itself evolved, all later transformations of the idea would retain this kernel of an idea: that we can understand the whole system by studying its most basic parts and how they interact.” In contrast, we provide examples of MMs’ ability to encapsulate a wide array of entity characteristics,

transcending simplistic part-to-whole relations. This capability allows MMs to eschew a rigidly mechanistic or reductionist ontology. In support, we explore examples of the evolution (diachronic shifts) and current state (synchronic shifts) of MMs in different disciplines, highlighting the fluid nature of metaphorical frameworks.

The pendulum: from simple machines to non-linear dynamical systems

Pendulums, those stalwarts of the mechanistic worldview, once epitomized the clockwork universe, ticking away in perfect harmony with Galileo's grand design. Galileo held that the timing of a pendulum's swing was an immutable constant, with the amplitude of its swing having no bearing on its period—a gentle swing would tick the seconds just as a more forceful one. A simple machine. This is also the philosopher of biology's usual spiel on pendulums: "Think of a mechanism as a dance of cogs and wheels, all neatly choreographed to return to their starting positions time and again, each part with its own little freedom to move" (Canguilhem 2008 [1992], 46). However, as Huyghens observed, pendulums can change their oscillations in response to external stimuli.⁷ With friction and air resistance, pendulums start doing their own thing, deviating from their expected path. Initially, these quirks were written off as 'noise.' But Huyghens noted a peculiar phenomenon: irrespective of their initial starting positions, two pendulums on clocks would invariably oscillate in perfectly opposing directions, like some cosmic game of mirror-mirror, a phenomenon now known as anti-phase synchronization. When one pendulum reached its apex on the right, the other mirrored it on the left, and this pattern persisted with unwavering consistency. This synchronized state emerged regardless of how the pendulums began their journey and continued unabated so long as the clocks shared a common supporting structure.

Fast forward to the latter half of the twentieth century. Huygens' pendulums represent an early and compelling instance of spontaneous synchronization across physical systems, a phenomenon that has since emerged as a central theme in various fields, including physics, engineering, biology, and neuroscience. It epitomizes the concept of coupled oscillators, wherein the dynamics of individual entities become entwined through interaction, leading to an emergent pattern of coordinated behavior. This highlights the profound interconnectedness that underlies even seemingly disparate systems, even in the case of the simplest machines. MM critics fall into a trap when they project simplicity onto machines that belies their behavioral complexity. Turns out, the plain pendulum's behavior is a microcosm of *deterministic chaos*, as Gleick (2011 [1987]), 43; added emphasis) noted:

Those studying chaotic dynamics discovered that the disorderly behavior of simple systems acted as a creative process. It generated complexity: richly

⁷ When Huygens mounted two pendulum clocks on a shared wall, he noted that the pendulums eventually synchronized their movements. He identified that minute vibrations from the wall, conveyed through the motion of one pendulum, influenced the other. This subtle interaction fine-tuned the swing durations, leading the pendulums to achieve synchrony over time.

organized patterns, sometimes stable and sometimes unstable, sometimes finite and sometimes infinite, but always *with the fascination of living things*.

The humble pendulum has morphed from a poster child of simple machinery into a diva of complex dynamics and behaviors. This transition, deeply rooted in the application of mathematical modeling and a systems-oriented perspective, paralleled a profound reconceptualization of organisms and other biological phenomena. Biological entities, too, began to be viewed not as isolated units but as dynamically integrated within and interacting with their environments.

This alignment in reconceptualization did not arise by mere chance. It was deliberately crafted and expanded upon within a metaphorical framework energized by the groundbreaking ethos of cybernetic research that burgeoned in the mid-twentieth century.

In “The nervous system as a physical machine,” cybernetics pioneer Ross Ashby (1947a) compared pendulum and animal, suggesting that both, when *viewed in their surroundings*, function as machines—or complex systems. We unpack Ashby’s take on this comparison: Ashby posited that pendulums, along with other complex systems, transcended mere collections of interacting parts, advocating for an approach where understanding one could illuminate the workings of the other.

First, Ashby (1947a, 56) defined an animal in an environment as a whole machine. The animal cannot be isolated from the environment:

Firstly, is the animal a “machine” in our sense? The animal by itself is incomplete, the environment being an essential part of the whole system. Without an environment, behaviour on the part of the animal would be both causeless and effectless. But when we have both animal and environment included, then the system is complete and the two form a machine in our sense. (It should be noted that we now make no essential distinction between the animal and its environment: both contribute to the organisation of the whole, both act dynamically on themselves and on the other, any equilibrium must stabilise both, and as physical systems the above principles must govern both).

Second, Ashby posited that any shift within the animal-environment duo should be interpreted as intrinsic to the system’s dynamics. Consider how an animal responds to its needs: eating to quell hunger, sleeping to recover from fatigue, or seeking cooler environments when overheating. This embodies the concept of equilibrium, where the system—comprising both the animal and its surroundings—naturally persists over time, ensuring the animal’s survival and adaptation within its habitat. Ashby described this dynamic, stating: “In all such cases the animal shows its adaptation by producing behaviour whose end result is to bring back these important variables after a disturbance” (1947a). This systems-perspective equilibrium does not require thermodynamic equilibrium or a steady state—only stable machine parameters. The parts themselves need not be.

Ashby applied the same ontology to pendulums. In much the same way that the parameters of the animal-environment hybrid typically result in some state at which the animal’s vital needs are met, the pendulum also tends toward a point at which

the ball is hanging down. “*It is an elementary property of all systems in equilibrium that they react so as to oppose disturbance*” (1947a; original emphasis). Ashby considered disturbance a deviation from rest, not a system function violation. A disturbance would occur if an animal became hungry, just as the pendulum if tapped. Still, the parameters of either machine would respond to a disturbance such that it remained at temporal equilibrium—equilibrium over time. Disturbance should also not be confused with ‘noise,’ as “*noise is in no intrinsic way distinguishable from any other form of variety*” (Ashby 1956, 186; original emphasis).

Ashby’s ontological analogy of pendulums and animals posits both as self-maintaining systems. He assumed that both systems might be under constant disturbance, but the pendulum ball continued to tend downward, whereas the animal continued to tend toward a state where its needs were met. He did not find this comparison at odds with organisms’ ability to self-organize and sought to demystify the mathematical underpinnings of how such self-organizing machines could operate (1941, 1947b).

One might argue that animals, unlike pendulums, possess the *teleological* capacity to adapt to environmental shifts (see the “[Purpose and agency](#)” section). Ashby answered by referencing “breaks”. Breaks happen when some variable exceeds a value possible for a physical machine. A pendulum string snaps, a gear melts, or an animal’s food source is decreased to the point that it can no longer sustain it—a new machine is formed. Such break conditions inherently redefine a system’s operating parameters. The ex-pendulum ball tends toward some other point, just as the animal tends toward some state where its needs *can* be met. In both cases, there is a physical change: for the pendulum, the string is no longer a factor, and it is rolling on the floor or bouncing off walls, whatever its new conditions are. The animal’s behavior changes as it adapts to its new environment. In both cases, the material itself is unimportant. What makes the system are the parameters—this is not “good old-fashioned substance metaphysics” (Nicholson 2018, 161) but a form of process ontology, which allowed Ashby, among other cyberneticists, to come to terms with the mechanistic modeling of the dynamicity of living causes.

Whether one shares Ashby’s view of pendulums is irrelevant. What is crucial is the cognitive richness that emerges from comparing pendulums to living systems. Ashby, upon contemplating a pendulum, did not just see a simple swinging object. He recognized a complex system mirroring the intricacies of an animal interacting with its environment, sparking a curiosity to explore the nature of both through comparative analysis. Ashby preempted many critiques leveled by contemporary MM critics, pointing out that both engineers and biologists stumbled when borrowing concepts from each other. For example, he noted that the comparison between a servomechanism and a cerebellum “was made unnecessarily difficult by the fact that the properties of servomechanisms *were described in words redolent of the automatic pilot, or the radio set, or the hydraulic brake*, while those of the cerebellum were described in words redolent of the dissecting room and the bedside” (1956, 4; added emphasis). Ashby argued that these challenges stemmed from the constraints of linguistic communication rather than any fundamental flaw in using MMs for analogical modeling, which often employs mathematical language. In observing any of these mechanical or organic devices, Ashby saw complex systems and offered

cybernetics as a language and ontology useful for any discipline to communicate with others productively.

This potential came to fruition in the 1970s when scientists began to identify instances of chaotic behavior—random yet intricately connected—across a wide range of seemingly unrelated fields: from the unpredictable patterns of weather and the irregular drip of a faucet to the rhythmic beating of the human heart. Beneath this apparent disarray, they discovered a concealed order, a discernible pattern that could be mathematically modeled using Dynamical Systems Theory (DST). Moreover, chaos, as conceptualized within DST, heralded a transformative approach to modeling in the life sciences. In ecology, particularly concerning the dynamics of animal populations, the critical role of nonlinear systems in nature came to the fore. Drawing on Robert May's pioneering work, ecologists apply chaos theory to shed light on the boom-and-bust cycles prevalent in populations, employing its mathematical tools of differential equations to articulate nonlinear growth and its limitations (Gleick (2011 [1987])). Similarly, the idea of dynamically coupled oscillators, which originated with the study of pendulums, now plays a pivotal role in modeling brain rhythms. This theoretical approach aids in understanding how various brain regions synchronize their functions to perform complex tasks (Buzsáki, 2006), including the processing of olfactory information—a complex process that once was dismissed as lacking sophistication, too, and that hinges on the coordinated activity of various neural circuits (Freeman and Skarda 1985; Barwich and Severino 2023).

The history of the pendulum offers two key insights. First, simple machines resist any single, static ontology, demonstrating the fluidity and diversity of conceptual foundations. Second, the process of identifying and selecting the essential attributes of objects of analysis is not a mere procedural step but a pivotal mechanism of scientific inquiry. This methodology promotes a dynamic interchange of insights, enhancing our understanding of entities that initially appear to diverge fundamentally.

The computational brain: machines as theories

We turn to the example of the brain-computer analogy. The computer, and 'computation' as a concept, evolved alongside notions of human intelligence and cognition. We clarify that the computer is modeled after the mental operations and the brain, and our understanding of it does not merely reduce it to its components, such as the lines of code that govern its operations. Historically, the fundamental comparison between the brain and the computer was never intended to hinge on such specifics. Comparisons centered on *the process of computation*. 'Computation' has undergone significant conceptual evolution, and so has 'the computer.' Like the pendulum, brain-computer comparisons do not imply any specific ontology.

Neuroscientists and philosophers have repeatedly taken aim at the brain-computer-metaphor (here in after BCM), scrutinizing the comparison for its potential oversimplification of the complexities inherent in neural processes. The modern concept of computation itself, which underpins this analogy, has roots stretching back to the work of intellectual giants like Turing, von Neumann, Wiener, and MacKay, whose work not only pioneered the fields of cybernetics and cryptography but

also influenced genetics and molecular biology (Kay 2000). Central to our exploration is the realization that equating the brain with a computer significantly leans on our interpretation of ‘computation,’ mirroring the diverse ways in which machines can be conceptualized:

If by ‘computer’ we mean ‘serial digital computer,’ then the answer is No. For the analogy between the brain and a serial digital computer is an exceedingly poor one in most salient respects. And the failures and similarity between digital computers and nervous systems are striking. On the other hand, if we embrace a broader conception of computation (...) then the answer is a definite yes. (Churchland et al. 1994, 26)

The concept of computation encompasses a wide spectrum, extending beyond digital calculations to include analog computation (Maley 2011), among other forms, such as connectionism (Clark 2000). While ‘computers’ are tangible entities, ‘computation’ represents a cognitive process not confined to mental operations alone. Rather than being preoccupied with the specific hardware makeup of a device (for instance, the electronic gadgets used to draft, exchange, and edit this document), computing is better understood as a theoretical framework of functional architecture that can be realized across a variety of physical forms, from machinery to other tangible entities (Newell and Simon 1976). This opens the door to computers being just about anything that can walk the computational walk—this includes humans, with their distinct cognitive capabilities (Daston 1994, 2022), proteins orchestrating cellular functions (Bray 2009), historical advances in mechanical constructs (Jones 2016), or engineered synthetic cells (Bongard and Levin 2023). The essence of computation transcends physical form, uniting a diverse array of entities that facilitate computational operations.

This understanding of computation aligns with the cyberneticists’ earlier perspective on machines, indicating that the parallels drawn between brains and computers, as well as between organisms and machines, hinge not on the tangible attributes of these entities but on the conceptual framework that views their functioning in terms of systems. This approach shifts the focus from the material specifics to the *operational dynamics* that characterize these entities.

The history of how brains were cast as the meat-space versions of computers uncovers a fascinating reversal of popular opinion. Commonly, one might anticipate that new technology is initially created and subsequently serves as a basis for comparison (Holt et al. 2021). But from the very beginning, the modern personal computer was designed to mirror the human mind and brain. Take McCulloch and Pitts (1943), who conceptualized the nervous system as embodying a form of logical calculus well before the era of modern computing and neural networks. Certainly, their goal was not to map out the brain’s *real* neural mechanisms but rather to construct a model that integrates biological plausibility with the brain’s capacity for mental operations. This endeavor sought to dismantle the barrier of mind–body dualism, creating a conceptual link between mental experiences and neural activities (Piccinini 2004, 203).

Specifically, Gigerenzer and Goldstein (1996) examine how the development of computational devices evolved not in isolation but as expressions of a particular

theory of mind, drawing on Daston (1994), who highlights the critical distinction made between intelligence and calculation in the nineteenth century. This distinction laid the groundwork for the burgeoning field of mechanical computing, exemplified by Babbage's exploration of mechanical computers as potential stand-ins for human computers (Gleick 2011). The historical roots of 'computation' reach much deeper, of course. Jones (2016) reminds us that the notion of computing machines and automata has roots pre-nineteenth century, notably in the work of Pascal and Leibniz. Thus, our aim is not to pinpoint a singular historical moment marking the inception of the computer metaphor for mind and brain but to highlight the key conceptual developments that underpin the modern BCM. These developments did not occur through a straightforward, linear progression from mechanical inventions to biological insights. Instead, they unfolded through a dynamic, bidirectional exchange that enhanced our understanding of each system by viewing each through the perspective of the other. Turing's work serves as a prime example of such reciprocal exchange. His insights into computational learning, initially inspired by child development studies (Turing 1950), subsequently informed psychological approaches to childhood education, illustrating a full-circle influence (McCorduck 1979).

Returning to the role of metaphors in science, in this compressed BCM zip-file history we identify three pivotal analogical applications. First, the *cognitive* role of Machine Metaphors (MMs) is highlighted through McCulloch and Pitts' innovative use of Boolean algebra to model the workings of neuronal processes. This application showcases how computational concepts can offer new insights into the biological mechanisms of the mind. Second, the *social* dimension of MMs comes to the fore, emphasizing that their adoption within the scientific community often depends on researchers' familiarity and comfort with the technologies in question. This aspect underscores the importance of tool usage in *further* shaping scientific thought and analogy-making. Third, MMs act as a conduit for *cross-disciplinary* synergy, enabling methodological and theoretical exchanges between fields that traditionally operated in isolation from one another, such as neuroscience and psychology or engineering and biology (as attempted by Ashby in 1956).

Overall, the story of MMs transcends mere tales of empirical breakthroughs and technological advancements that, once their purpose is allegedly outlived, ought to be discarded. As illustrated by the evolution of the BCM, there has been a profound shift in how we conceptualize 'the mental' and its neural foundations, alongside our understanding of computers as tools or devices.

Discussion

So, what is a machine anyway? This question, along with its myriad answers, is in a state of perpetual flux. Over time, scientific perspectives on machines have varied widely, encompassing roles as diverse as theoretical models, proxies for human intellect, embodiments of complex systems, or even direct analogs to biological processes through robotics and biobots. The "[Metaphorical analogies in science](#)" section of our discussion highlights that the essence of a metaphor lies not in the literal characteristics of the entities compared, but in the traits that researchers consider

crucial for a meaningful comparison. Hence, “machines,” in whichever way we conceptually slice them, open up a vast landscape of ontological, heuristic, and communicative possibilities, sidestepping the motivation to focus on those machine traits that just do not jive with our *current* conceptualizations of living things.

Our core message is that applying MMs, when approached with an understanding of their dynamic potential, opens significant pathways for exploring the complexities inherent in biological systems. Instead of ensnaring biological phenomena within an inflexible mechanical paradigm, MMs catalyze a meaningful exchange across disciplines, including engineering and biology. This refined perspective challenges their outright rejection. We uphold that as our comprehension of technology and biology progresses, our metaphors must also adapt, fostering an enriching interplay that deepens our understanding of both machines and living causes.

What does this mean for the MM critic? Nicholson (2021) is right to argue that as our knowledge of life and of thermodynamics evolve, we should be willing to update (the ontological foundation of) our metaphors, too. But when Nicholson (2018) floats the idea that perhaps a wildfire or a meandering stream (or pick your poetic natural process; he’s not fussy) might outshine *any* machine metaphor, he misses a key point: our notions of what machines *can do* and what they *are doing* evolve right alongside our knowledge of life, keeping pace with our deepening insights into the biological realm. So, as our machines and conceptualizations of machines evolve, we should be willing to update our metaphorical frameworks, including their philosophical analysis. The reciprocal conceptual evolution between machines (or machine-concepts) and living causes (“[Reciprocity of the machine metaphor](#)” section) is key, and as machines continue to change as objects of inquiry themselves, we find no reason why MMs cannot continue to adapt. The remarkable changeability of machines is what makes MMs useful. We find that machines offer a remarkably wide variety of possible comparisons, only some of which are problematic, just as any comparison could be.

We conclude with two constructive suggestions. First, stop saying *the* machine metaphor. There is no such *the*. Second, critics of MMs have stressed the importance of representing the dynamic and coupled processes inherent in living systems. Throughout this paper, we have highlighted how such a focus aligns with existing modeling approaches in both robotics and biology. Dynamical Systems Theory (referenced in “[Non-linear dynamics and processualism](#)” and “[The pendulum: from simple machines to non-linear dynamical systems](#)”) serves as a powerful mathematical framework for articulating the temporal evolution of systems. Its utility extends far beyond complicating philosophical intuitions about pendulums; it renders the dynamicity of biology tractable. Take, for instance, the Lotka-Volterra equations, a seminal model delineating the interplay between predator and prey populations over time. Similarly, the Wilson-Cowan model elucidates the interactions between populations of excitatory and inhibitory neurons, while the Goodwin model explores feedback mechanisms in circadian rhythms, and the Kronauer Model sheds light on the complexities of sleep regulation. Invoking the image of a river won’t advance our understanding of how proteins bind. However, employing differential equations to capture the dynamics of protein binding can indeed shed light on this process. Furthermore, DST does not corner MM critics into revising their staunch ontological

stance that organisms fundamentally differ from machines. Crucially, DST, by itself, makes no claims about the *ontology* of any phenomenon; it is a mathematical apparatus for modeling specific behaviors or processes (Beer 2023). By highlighting the convergence of philosophical arguments and existing research with DST, we provide process thinking with a tangible pathway into scientific modeling, prompting the question (aligning with Bechtel and Abrahamsen 2013): how does DST, as a mathematical framework, enhance our theoretical understanding of biological systems in a way that mirrors, and potentially enriches, our understanding of mechanical systems and vice versa?

The supposed clash between MMs and process ontology does not really hold water, backed up by evidence from both the modern lab bench and the annals of history. So, rather than giving MMs the cold shoulder, we are advocating for reshaping and embracing their potential in the scientific sandbox. Machines are part and parcel of our world; dodging comparisons is not an option. Instead, let's ensure these analogies do the heavy lifting they are capable of.

Acknowledgements We express our gratitude to the participants of the “Philosophy and Neuroscience at the Gulf IV” workshop, particularly Carl Gillett and Edouard Machery, for their insights on an earlier version of this argument. We also appreciate the constructive feedback from anonymous reviewers and the editor.

Funding No funding sources are available.

Declarations

Conflict of interest The authors declare no conflict of interest.

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